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Performance of sewage treatment plants and impact of effluent discharge on receiving water quality within an urbanized area

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Abstract In Brazil, wastewater treatment coverage is low. Even when treatment is carried out, many municipalities cannot achieve adequate levels of contaminant removal, and the usual practice of releasing raw or treated domestic effluent into water bodies remains. Thus, this pollution source puts pressure on water resources, compromising downstream uses of the disposal. This study has two aims: (1) to evaluate the performance of sewage treatment plants and (2) to determine the impact of discharging treated effluent on the water quality of receiving water bodies located within an urbanized area in the Velhas River basin, Minas Gerais State, Brazil. Monitoring data from raw wastewater were compared with typical ranges reported in literature, and effluent concentrations were compared between plants. The monitoring data of the receiving water bodies collected at points upstream and downstream of each disposal were statistically compared. Different performances between the systems and significant alterations in the receiving bodies resulting from the discharge of the treated effluents were found.

Keywords Belo Horizonte Metropolitan Region · Domestic effluent · Recipient water bodies · Performance evaluation · Surface water quality · Velhas River basin

Introduction

In Brazil, domestic effluent generated by 45% of the urban population is untreated. It is estimated that more than 5.5 thousand tons of biochemical oxygen demand (BOD) can reach Brazilian water bodies per day considering the residual sewage loads, the state of existing collection and treatment infrastructure, and the efficiency of the processes employed (ANA, 2017). Even when treatment is carried out, many municipalities experience problems in terms of design, operation, and maintenance of sewage treatment plants (STPs), which hinder them from achieving their proposed objectives, namely, the removal of solids and organic matter (von Sperling, 2016). Thus, frequent monitoring of influent and effluent concentrations of the systems is needed in order to detect early the cause of possible problems and operational failures that could negatively affect the process (Liu et al., 2014). Such monitoring could possibly improve the performance of the STPs (Collivignarelli et al., 2018).

Several studies have analyzed the performance of STPs operating at full-scale in several countries

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(Alderson et al., 2015; Colmenarejo et al., 2006; Espinosa et al., 2016; Niku et al., 1981; Oliveira & von Sperling, 2008, 2009, 2011; Qi et al., 2020; Sun et al., 2016). However, few studies have collectively analyzed the monitoring data of the receiving bodies of the STPs (Comber et al., 2020; Momba et al., 2009), and especially few have considered the hydrographic basin in which they are located (Leonel, 2016). In addition, there is limited availability of studies or information more generally regarding STPs operating at full-scale in Brazil (Leonel, 2016; Oliveira & von Sperling, 2011). Thus, it is essential to evaluate the effectiveness of treatment systems in operation in Brazil.

There are 3668 STPs in Brazil; most of these STPs use anaerobic reactors (representing 37% of the systems), primarily upflow anaerobic sludge blanket (UASB) reactors, that may or may not be followed by post-treatment. Stabilization ponds (35%) constitute the second most widely used technology in Brazil. Other less popular processes that are utilized include simplified processes (such as septic tank systems) (12%) and activated sludge (10%) (ANA, 2020). Thus, there is a great diversity of secondary-level treatment technologies in the country; however, less than 5% of the STPs have been designed to remove nutrients (ANA, 2017).

Thus, in the context of low wastewater treatment coverage, as well as insufficient treatment (if any) in some municipalities, there is a compromise in water resource quality (ANA, 2012; ANA, 2013). In Brazil, according to the National Water Agency (ANA, 2017), the regions most affected by the discharge of wastewater are dense urban areas.

Given this context, this study aims to assess the performance of sewage treatment plants and the impact of discharging treated effluent on the water quality of receiving water bodies within an urbanized area of an important Brazilian catchment. Sewage treatment plants that employ treatment technologies typically adopted across Brazil were selected to understand the effectiveness of STP performance in Brazil.

Methods

Study area

The Velhas River basin is located in the state of Minas Gerais, Brazil, and comprises an area of 27,850 km^2. It encompasses 51 municipalities, 44 of which have their urban areas within the perimeter of the basin. The total resident population in the basin was approximately 4.4 million in 2010, i.e., 24.7% of the total population of the state (CBH Rio das Velhas, 2015), with a population density of 164.04 residents/km^2 (IGAM, 2014). The Velhas River basin is located in the São Francisco River hydrographic basin, the largest basin entirely located in Brazil, occupying 8% of the national territory and bearing great socioeconomic importance for the country (CBHSF & ANA, 2004).

A part of the Belo Horizonte Metropolitan Region (BHMR) is located in the upper course of the Velhas River basin, with the largest population and the highest concentration of economic activities in the watershed (CBH Rio das Velhas, 2015). Of the 51 municipalities in the basin, 15 are in the BHMR. Although this region occupies only 10% of the area of the Velhas River basin, approximately 70% of the watershed population reside within its limits (Pinto et al., 2019).

The BHMR is the third-largest metropolitan region in the country. It had a gross domestic product (GDP) of 180.535 billion BRL in 2017 (IBGE, 2017), i.e., approximately 55 billion USD that year, which corresponded to 31% of the GDP of the Minas Gerais State. Despite great economic development, the BHMR suffers the greatest contamination by domestic and industrial effluents within the Velhas River basin region (Calazans et al., 2018; Pinto et al., 2019). On the one hand, the index of the population served by sewage collection without treatment at the BHMR amounted to 17% in 2013. On the other hand, the index of the population served by both collection and treatment was 67% (adapted from ANA, 2017).

Database

The sanitation service provider provided the monitoring data of 14 STPs in operation in a part of the BHMR in the Velhas River basin. Figure 1 shows the location of the systems. Table 1 shows the characterization of the 14 STPs under study, which includes the treatment process adopted, the design flow, and the range of influent flows during the study period (at 5–95% percentiles). A higher prevalence of UASB reactor technology was observed, mainly with regard to post-treatment using a trickling filter, in accordance with what is commonly

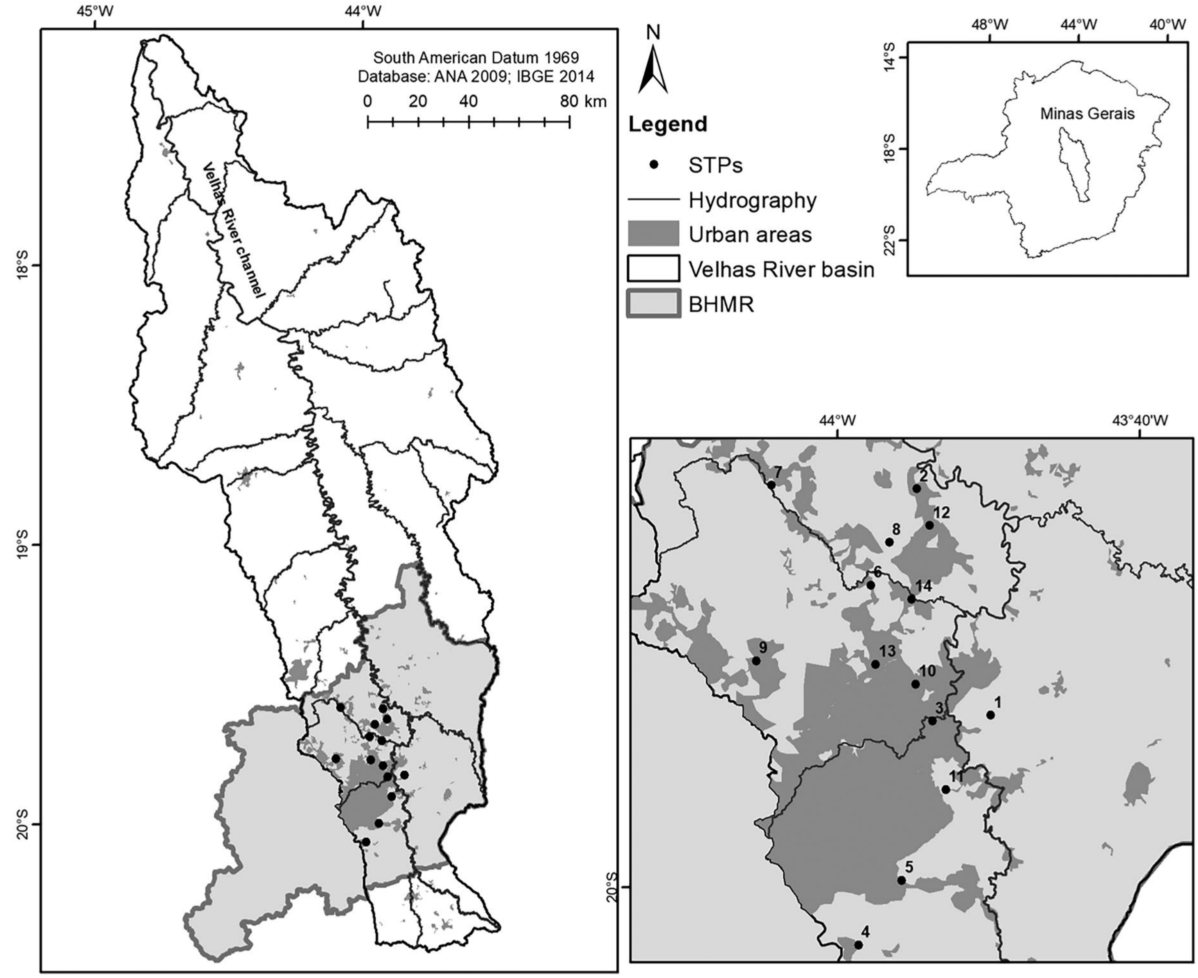


Fig. 1 Location of the 14 selected STPs in the Velhas River basin, Minas Gerais, Brazil

used throughout Minas Gerais State (Chernicharo et al., 2018) and the nation (Chernicharo et al., 2015; ANA, 2020).

Electronic spreadsheets were organized with the entire scope of the data, in chronological order, containing information on raw and treated wastewater as well as on the receiving water bodies upstream and downstream of the releases. The monitoring period covered was from 2011 to 2016.

For the influent and final effluent wastewater of the STPs, various parameters, namely biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), pH, total ammonia nitrogen (NHx), nitrate (NO_3), total phosphorus (P), and *Escherichia coli* (*E. coli*), were evaluated.

The receiving water bodies from the 14 STPs are streams and rivers. The parameters analyzed in the monitoring of these bodies (both upstream and downstream of disposal) were BOD, COD, dissolved oxygen (DO), turbidity, pH, NHx, NO_3, P, and *E. coli*. These parameters were selected based on the data made available by the sanitation service provider.

Table 2 presents the distances between the disposal point and the upstream and downstream monitoring points for each STP. According to the sanitation service provider, the locations of the monitoring points were based on the access conditions to collection sites and the need to have no other forms of discharge between the effluent disposal and downstream monitoring sites.

Table 1 Characterization of 14 sewage treatment plants in the Velhas River basin

STP	Treatment process	Acronym	Design flow (L/s)	Inflow rate (percentile 5%) (L/s)	Inflow rate (percentile 95%) (L/s)
1	Upflow anaerobic sludge blanket (UASB) reactor	UASB	3.7	1.1	1.7
2	UASB + Dissolved air flotation (using ferric chloride as a coagulant)	UASB + DAF	20.0	8.1	18.4
3	UASB + Trickling filter	UASB + TF	1800.0	1060.4	1777.0
4	UASB + Trickling filter	UASB + TF	9.5	14.0	20.9
5	UASB + Trickling filter	UASB + TF	25.0	24.1	48.6
6	UASB + Trickling filter	UASB + TF	37.4	13.1	33.1
7	Anaerobic pond + Facultative pond	ANP + FP	38.7	13.2	25.9
8	Facultative pond + Maturation pond	FP + MP	8.4	4.1	6.8
9	Facultative pond	FP	18.6	7.0	28.7
10	Facultative aerated pond	FAP	110.0	4.5	110.0
11	Conventional activated sludge	CAS	2250.0	1977.0	2561.0
12	Extended aeration activated sludge	EAAS	126.0	28.8	61.5
13	Extended aeration activated sludge	EAAS	21.0	23.1	33.9
14	Extended aeration activated sludge	EAAS	90.0	32.4	76.9

Evaluation of the performance of sewage treatment plants and the impact of effluent discharge on the water quality of receiving water bodies

Concentrations for all parameters in the influent to the STPs were compared with the typical concentration ranges found in raw domestic sewage in developing countries, as reported by von Sperling and Chernicharo (2005). Considering the data on the effluent concentrations of each parameter, the Kruskal–Wallis non-parametric test was applied (Kruskal & Wallis, 1952), followed by the Dunn multiple comparison test where applicable (Dunn, 1964), at a 5% significance level. Such analysis was carried out to compare the operational performances among the STPs. Removal efficiencies were calculated based

Table 2 Distances between the effluent discharge point and upstream and downstream monitoring sites for each STP

STP	Distance from effluent discharge point to upstream monitoring site (m)	Distance from effluent discharge point to downstream monitoring site (m)
1	20	60
2	180	115
3	360	100
4	30	40
5	60	60
6	45	80
7	300	300
8	12	85
9	35	20
10	20	40
11	1900	1800
12	50	26
13	20	260
14	25	45

Table 3 Standards for the discharge of municipal wastewater established by the Normative Deliberation COPAM/CERH-MG n. 01/2008

Parameter	Permissible limit values
BOD	Maximum effluent concentration of 60 mg/L, or removal efficiency of at least 60% (with an annual average of ≥ 70%)
COD	Maximum effluent concentration of 180 mg/L, or removal efficiency of at least 55% (with an annual average of ≥ 65%)
TSS	Maximum effluent concentration of 100 mg/L (or 150 mg/L for stabilization ponds)
pH	Between 6.0 and 9.0

on the influent and effluent loads for each STP (i.e., influent and effluent concentrations multiplied by the flow rate) for BOD, COD, TSS, NHx, and P.

In Minas Gerais, the State Environmental Policy Council (COPAM) and State Water Resources Council (CERH) Normative Deliberation n. 01/2008 specifies the standards for effluent discharge. Violation percentages were calculated for the parameters monitored in the STPs that have standards in the legislation (Table 3).

Regarding the monitoring data of the receiving bodies, for each system and variable, the Mann–Whitney non-parametric test (Mann & Whitney, 1947) was applied at a 5% significance level, to compare the data gathered upstream and downstream and to verify the possible impacts resulting from the disposal from each STP. Statistical tests were conducted using Statistica® 10.0 software.

In Brazil, inland water bodies are classified into rating classes, where each class has target values for water quality parameters. These targets must be achieved in order to maintain the quality of these water bodies and be compatible with various types of locally predominant water use. In addition to complying with discharge standards, the effluent must also comply with the specific standards for the class relevant to the receiving water body. Deliberation COPAM/CERH 01/2008 also considers the water quality standards for each rating class. The violation percentage was calculated for each receiving water body, upstream and downstream of the STP effluent discharge points, based on the water body rating and according to the legally established limits (Table 4).

Results and discussion

Operational performance of sewage treatment plants

Based on the data made available by the sanitation service provider for raw and treated wastewater, the sampling frequency for each parameter for each STP differed. Table 5 details the number of data samples resulting from these differing monitoring frequencies for each plant and each parameter. In sum, 8982 influent and effluent data samples from all 14 STPs were analyzed.

Table 4 Water quality standards for each rating class established by COPAM/CERH-MG n. 01/2008, based on the parameters in focus for this study

	Permissible limit values		
Parameter	Class 1	Class 2	Class 3
BOD (mg/L)	3	5	10
DO (mg/L)[a]	6	5	4
Turbidity (NTU)	40	100	100
pH	6.0 to 9.0	6.0 to 9.0	6.0 to 9.0
E. coli (MPN/100 mL)	200	1000	4000
NHx (mg/L)	3.7 for $pH \leq 7.5$	3.7 for $pH \leq 7.5$	13.3 for $pH \leq 7.5$
	2.0 for $7.5 < pH \leq 8.0$	2.0 for $7.5 < pH \leq 8.0$	5.6 for $7.5 < pH \leq 8.0$
	1.0 for $8.0 < pH \leq 8.5$	1.0 for $8.0 < pH \leq 8.5$	2.2 for $8.0 < pH \leq 8.5$
	0.5 for $pH > 8.5$	0.5 for $pH > 8.5$	1.0 for $pH > 8.5$
NO_3 (mg/L)	10	10	10
P (mg/L)[b]	0.1	0.1	0.15

[a] For DO, the standard refers to the minimum threshold value

[b] Standard for lotic systems

Table 5 Number of data samples by STP and by parameter, for raw sewage (R) and treated effluent (T)

STP	BOD[a]		COD[a]		TSS[a]		pH[a]		NHx[b]		NO_3[b]	P[b]		*E. coli*[c]		Total
	R	T	R	T	R	T	R	T	R	T	T	R	T	R	T	
1	59	59	60	60	60	60	60	59	12	12	10	12	12	30	30	595
2	59	58	60	59	60	59	59	60	12	12	12	12	12	31	30	595
3	60	60	60	60	60	60	60	60	60	60	55	60	60	56	57	888
4	60	60	60	60	60	60	59	60	13	13	14	14	14	31	31	609
5	60	60	60	60	60	60	60	54	14	14	13	14	14	30	30	603
6	60	60	60	60	60	60	60	60	14	14	14	14	14	31	31	612
7	60	60	59	59	60	60	60	60	12	12	12	12	12	29	29	596
8	60	60	60	60	60	60	60	60	12	12	12	12	12	30	30	600
9	59	59	58	59	59	59	55	55	11	11	11	11	11	30	30	578
10	58	58	58	58	59	58	58	60	12	12	12	12	12	28	29	584
11	59	59	59	59	59	59	59	59	59	59	57	58	58	58	58	879
12	60	60	60	60	60	60	60	60	12	12	12	12	12	30	30	600
13	59	59	60	60	60	60	60	60	12	12	12	11	12	30	30	597
14	60	60	60	60	60	60	60	59	21	21	21	21	21	31	31	646
Total	833	832	834	834	837	835	830	826	276	276	267	275	276	475	476	8982

[a] Monthly monitoring frequency

[b] Biannual/monthly frequency depending on the STP

[c] Bimonthly/monthly frequency depending on the STP

Figure 2 shows the concentrations of the analyzed parameters in raw wastewater and the typical range of raw domestic sewage reported by von Sperling and Chernicharo (2005).

Nine of 14 STPs showed an influent concentration of organic matter (i.e., BOD and COD) within the usual range. More concentrated raw effluent than what is usually reported was found at STP-1, STP-4, and STP-7, with their medians above the upper limits. Possible explanations for the higher concentrations observed are lower per capita water consumption, industrial contributions, type of sampling, and lower return coefficients, which should be investigated individually for better understanding of their impact (Leonel, 2016; Monteiro, 2009; Oliveira & von Sperling, 2005, 2011; Silva Filho, 2007).

Twelve of 14 STPs had influent TSS concentrations within the usual range, that is, from 200 to 450 mg/L (von Sperling & Chernicharo, 2005). STP-5 and STP-12 showed low influent BOD, COD, and TSS concentrations, indicating more diluted sewage. The sewage collection systems in Brazil are designed as absolute separator systems, where sewage should be collected, transported, and treated separately from rainwater. In practice, this does not always occur; there are connections between sewage and rainwater systems, mainly through clandestine connections or accidental interceptions (Oliveira et al., 2020). The lowest concentrations in the sewage that reaches STP-5 and STP-12 may occur due to rainfall contributions that dilute the raw sewage.

The pH values were found to be within the typical range as reported by von Sperling and Chernicharo (2005), i.e., from 6.7 to 8.0. Colmenarejo et al. (2006) found that STPs in Spain had an average influent pH of 7.5. Silva Filho (2007) and Monteiro (2009) studied STPs located in another region of Brazil. While Silva Filho (2007) discovered that pH values were well-adjusted to the range described in the literature, Monteiro (2009) found slightly higher values.

Espinosa et al. (2016) pointed out that NHx monitoring has been seldom practiced in sewage treatment plants, probably because the laws do not always require the monitoring of this variable. In fact, in studies that have analyzed the performance of STPs in operation in Brazil, not all have included this parameter. Moreover, in the studies which did include NHx monitoring (Espinosa et al., 2016; Leonel, 2016; Silveira, 2011), only the effluent concentrations of the STPs were evaluated. Colmenarejo et al. (2006) observed lower influent NHx concentrations for operating STPs in Spain, with an average of 18.5 mg/L. Sun et al. (2016) found that influent NHx concentrations ranged from 13.0 to 40.0 mg/L in 3340 STPs in China; these concentrations were lower than those measured in the Velhas River basin.

STPs in the Velhas River basin show influent concentrations of P within the usually expressed range for raw sewage (Fig. 2), which corroborates what was observed by Oliveira (2006), Leonel (2016), and Sun et al. (2016). Qi et al. (2020) found lower P concentrations for STP influent in China, with an average of 3.2 mg/L. The plants in the Velhas River basin also showed influent concentrations within the typical range of raw wastewater in developing countries for *E. coli* (10^6 to 10^9 MPN/100 mL), which is considerably wide (Oliveira & von Sperling, 2005). In terms of evaluating the influent concentrations of thermotolerant coliforms, several authors have likewise found values within the expected range for raw domestic effluent (Espinosa et al., 2016; Monteiro, 2009; Oliveira, 2006; Silva Filho, 2007).

Figure 3 shows the effluent concentrations of the analyzed parameters of the STPs. Using the Kruskal–Wallis test ($p < 0.05$), significant differences were identified among treatment plants, with regard to all parameters. Effluent BOD concentrations were significantly higher at STP-2 (UASB + DAF, designed to treat 20.0 L/s) and STP-4 (UASB + TF, designed to treat 9.5 L/s) and did not differ significantly from each other. Effluent COD concentrations were likewise high in these two STPs. As shown in Table 1, STP-4 presented a great hydraulic overload from 2011 to 2016, in which even the minimum influent flows (at the 5% percentile) exceeded the design flow. According to Almeida et al. (2018), the hydraulic overload of STPs with UASB reactors is one of the factors responsible for the loss of quality of the final effluent. Compact processes, with a few hours of detention (e.g., UASB reactors) tend to be more sensitive and may lead to drag and loss of system biomass (von Sperling & Chernicharo, 2005). The large interquartile range of effluent BOD and COD concentrations from STP-2 indicates instability in the system and possible problems in operation, construction, and design.

Although the inclusion of a post-treatment step to the UASB reactor can improve effluent quality in terms of solids and organic matter (Oliveira & von Sperling, 2009), STP-1 failed to exhibit significant differences compared to the other facilities (i.e., STP-2 and STP-5 for BOD and COD; STP-5 and STP-6 for TSS). Moreover, STP-1 showed effluent concentrations significantly lower than those of STP-4 for BOD, COD, and TSS and those of STP-2 for TSS. According to Almeida et al. (2018), several Brazilian STPs have serious difficulties with regard to sludge management; this is one of the main contributors to the loss of quality of effluents from treatment plants that contain UASB reactors in their processes. This is because biomass is lost along with the effluent, thereby increasing the concentrations of solids and organic matter. Thus, it is necessary to investigate the management of the solid phase in the systems located in the Velhas River basin.

Although Brazilian treatment plants are designed to remove organic matter, high concentrations are still observed in the final effluent. Sun et al. (2016) evaluated monitoring data from 3340 STPs in China and found that the median BOD and COD concentrations in the effluent were 8.3 and 30.0 mg/L, respectively. Qi et al. (2020) evaluated 1822 STPs in China and found that the effluent had BOD and COD concentrations lower than 20.0 and 50.0 mg/L, respectively, in all STPs. Comber et al. (2020) found that the BOD concentrations in effluent were below 8.0 mg/L in 180 STPs in England.

During the evaluation of treatment type with the greatest number of STPs (UASB + TF), great variability in effluent BOD, COD, TSS, and NHx concentrations across treatment plants was found (Fig. 3). Alderson et al. (2015) likewise reported a high variability in the performance of STPs operating the same process due to differences in the operating conditions. Under the intended operations, systems of the same treatment type are expected to behave similarly. On the one hand, higher effluent concentrations were found in STP-4 due to the hydraulic overload in this system, as mentioned earlier. On the other hand, the lowest effluent concentrations were found in STP-3, the largest sewage treatment plant of UASB + TF (design flow of 1800 L/s; Table 1). The better performance of STP-3 is related to superior operational control of the larger system, ensuring that it achieves the expected performance for the technology employed. In Brazil, many small- and medium-sized STPs experience technical and financial resource limitations (Noyola et al. 2012).

The sewage treatment plants with the lowest concentrations of organic matter and TSS were those of activated sludge, mainly STP-13 and STP-14. The process leads to high effluent quality. Moreover, the extended aeration variant is the most efficient in terms of removing BOD due to the almost total assimilation

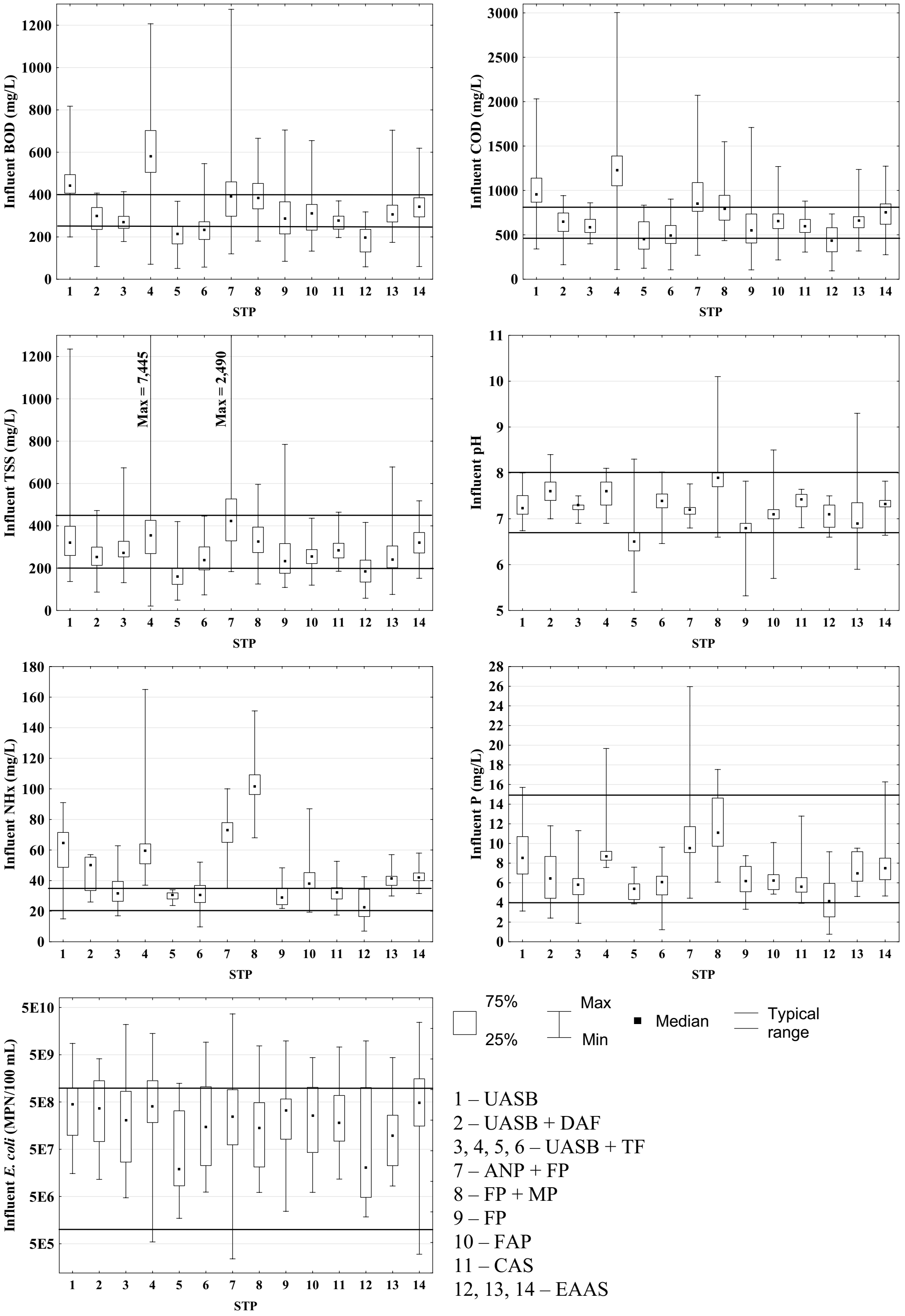


Fig. 2 Influent concentrations of selected parameters at 14 STPs in the Velhas River basin

of the substrate in the aeration tank (von Sperling, 2007a). Among the various treatment technologies analyzed by von Sperling and Oliveira (2009), the activated sludge process exhibited the best performance with regard to the removal of organic matter. Colmenarejo et al. (2006) observed that activated sludge treatment plants provided greater stability in operation compared to other forms of treatment.

Regarding TSS, the highest effluent concentrations were found at STP-2 (UASB + DAF), STP-4 (UASB + TF), STP-7 (ANP + FP), STP-8 (FP + MP), and STP-9 (FP). STP-2 and STP-4, which both use an UASB followed by post-treatment, likewise showed high effluent BOD and COD concentrations. Therefore, the TSS results reinforce the operational problems experienced by these systems (i.e., loss of biomass) and consequently the loss of solids and organic matter in the treated effluent.

STP-7, STP-8, and STP-9 comprise different stabilization pond configurations, which include facultative ponds for sewage treatment. In this process, the necessary oxygen for aerobic respiration of the bacteria is supplied via photosynthesis performed by the algae. Due to the presence of algae, this process may lead to high concentrations of TSS in the treated effluent (Espinosa et al. 2016; von Sperling, 2007b). The significantly lower concentrations observed in STP-10, compared with STPs with ponds, are due to the use of aerators in the facultative aerated pond (von Sperling, 2007b).

Effluent pH from all STPs were between 6.0 and 9.0, with values close to those found in the STPs studied by Monteiro (2009), Silveira (2011), and Ismail (2013). The highest median values in the Velhas River basin were identified in STP-8 and STP-9, which are systems with stabilization ponds, in which, according to von Sperling (2007b), there is CO_2 consumption with a consequent increase in pH due to photosynthesis carried out by algae. In addition, during the day and the hours of maximum photosynthetic activity, the pH can reach values around 10.0 (von Sperling, 2007b), with an even higher value (11.3) observed in STP-9.

The highest effluent NHx concentrations were observed in the STPs with UASB reactors, both with and without post-treatment. In STPs 1, 2, 4, and 5, concentrations in treated effluent were found to be much higher than those typical for raw wastewater, ranging from 20 to 35 mg/L (von Sperling & Chernicharo, 2005). According to Almeida et al. (2018) and Bressani-Ribeiro et al. (2018), the non-removal of NHx in UASB is inherent to the system and does not necessarily indicate problems with the design, construction, or operation of the units.

The lowest NHx concentrations were observed in the STPs with stabilization ponds and activated sludge processes. In stabilization pond systems, some mechanisms that promote the removal of NHx are the volatilization of ammonia (most important in maturation ponds), the ammonia assimilation by algae, and nitrification (von Sperling, 2007b). With regard to the NHx concentrations of wastewater treated by stabilization ponds in the Velhas River basin, Silveira (2011) and Leonel (2016) found similar values in the STPs of their studies. In activated sludge treatment plants operating in Brazilian climatic conditions (i.e., at high temperature), nitrification takes place almost systematically (von Sperling, 2007a). In all STPs, low effluent NO_3 concentrations were observed.

Technologies adopted in the STPs examined in this study are not designed for phosphorus removal, except flotation. The highest effluent P concentrations were found at STP-1, STP-4, STP-7, and STP-8, with values close to the range reported in the literature on raw wastewater, from 4.0 to 15.0 mg/L, according to von Sperling and Chernicharo (2005). Comber et al. (2020) studied 170 STPs in operation in England. They found that the mean monthly P concentrations for all STP effluents varied between 1.7 and 2.5 mg/L. Qi et al. (2020) found that the average P concentration in the effluent in STPs in operation in China was 0.5 mg/L. These results confirm that in Brazil, STPs are not designed to remove this nutrient.

The lowest median P concentrations were found in STP-2, STP-11, STP-12, STP-13, and STP-14. In flotation, it is possible to remove the phosphorus present in suspended solids, given that it is a physico-chemical process (Aisse et al., 2001; von Sperling & Chernicharo, 2005). According to Aisse et al. (2001), substantial phosphorus removal can be achieved using common coagulants, such as aluminum sulfate and ferric chloride, the latter having been used in STP-2. Among the different treatment processes analyzed by Oliveira and von Sperling (2011), the STPs with activated sludge had the lowest effluent P concentrations.

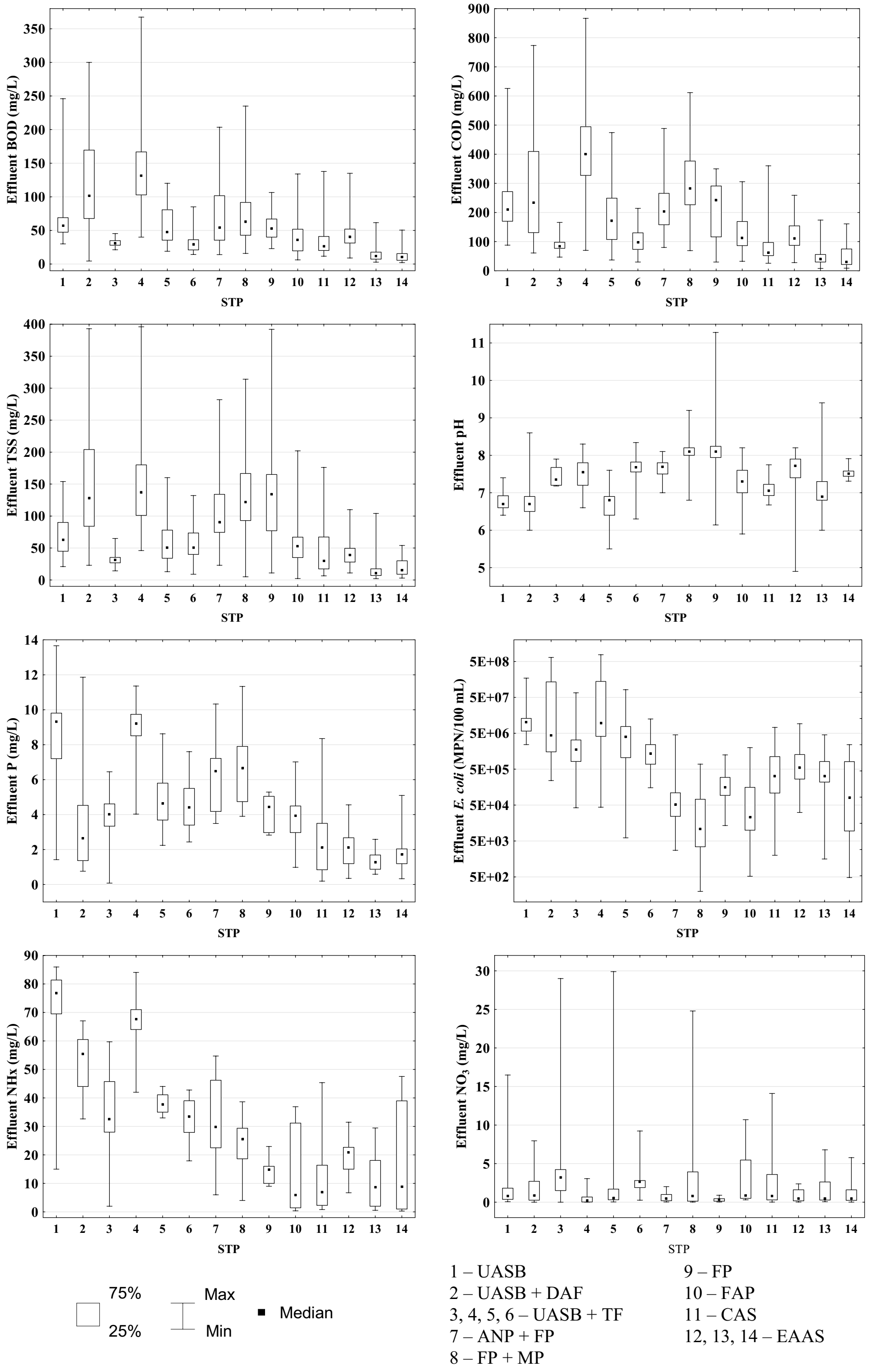


Fig. 3 Effluent concentrations of selected parameters at 14 STPs in the Velhas River basin

High effluent *E. coli* concentrations were observed in several STPs. The lowest medians were found in the STPs that employed stabilization ponds. In these systems, especially in the maturation ponds, some mechanisms responsible for the removal of pathogenic organisms were determined to be temperature, solar radiation, pH, food shortage, and high concentration of dissolved oxygen (von Sperling & Chernicharo, 2005).

Figure 4 presents the violation percentage according to the local legislation for wastewater discharge (Table 3); the most violated parameters were BOD, COD, and TSS. The STPs that violated most standards were STP-2, STP-5, STP-4, STP-8, and STP-9; these results also align with the statistical analysis results that show poorer performance from these plants.

Removal efficiencies were calculated based on the influent and effluent loads of the STPs, and these results are illustrated in Fig. 5. STPs that had higher effluent concentrations, mainly STP-2 and STP-4, also had a lower removal rate of the BOD, COD, TSS, and NHx loads. Negative load removal efficiencies were reported for all parameters, highlighting that STPs with UASB reactors (i.e., STP-1 to STP-6) were in the 75th percentile below zero for NHx load removal (Fig. 5).

Impact of effluent discharge from STPs on the water quality of receiving water bodies

Monitoring of receiving bodies is more frequent in STP-3 and STP-11, in which BOD, COD, DO, turbidity, pH, and *E. coli* are monitored monthly and NHx, NO_3, and P are monitored quarterly. In the other systems, monitoring is conducted bimonthly for BOD, COD, DO, turbidity, pH, and *E. coli* parameters. The nutrients (i.e., NHx, NO_3, and P) are monitored every 6 months. The sampling of all receiving bodies upstream and downstream of the disposal resulted in a total of 6553 samples gathered and analyzed.

Table 6 shows the results of the Mann–Whitney test, which compares the upstream and downstream values of the release of each STP for each parameter. Figures 6 and 7 show the box plots of BOD, COD, DO, and turbidity values, and pH, NHx, NO_3, P, and *E. coli* values, respectively, upstream and downstream of each disposal. The STPs highlighted in the figures are those in which there was a significant difference between the upstream and downstream values, as shown in Table 6.

Although STPs are used to regulate the discharge of untreated effluents, the treated wastewater still imposes physical, chemical, and biological changes to the receiving systems. Treated effluent does not have the same quality as that of the receiving watercourses and may cause significant impacts (Carey & Migliaccio, 2009; Comber et al., 2020; Drury et al., 2013). This situation is identified in the Velhas River basin based on the results of this study. The parameters that exhibited the highest percentage of disposals that caused a significant change in the quality of the receiving water bodies were BOD, P, and *E. coli*. For these variables, at least half of the receiving bodies had significantly higher concentrations downstream than those upstream (Table 6). Thus, a compromise in water quality in terms of organic matter, nutrients, and indicators of pathogenic organisms manifests as an effect on the release of treated effluents. Momba and Sibewu (2009) identified a relationship between the water quality of the discharged effluent and that of the receiving water bodies downstream of the discharge point for four STPs in South Africa. The authors identified impacts in terms of BOD, OD, P, and pathogenic microorganisms.

With regard to BOD and COD, the receiving water bodies in which there was a significant increase in downstream concentrations are related to the STPs that had the highest concentrations of the parameters in the treated effluents. Conversely, the receiving bodies in which no impact was identified and those where the concentrations were even significantly lower downstream were found to be from the STPs with the lowest effluent concentrations of organic matter. However, this situation was not consistently observed for the other parameters and was not observed in all instances, considering that, in some cases, it is not possible to establish a direct relationship between the operational performance of the STP and the water quality because of the different hydrodynamic conditions of the receiving bodies.

Unfortunately, there was no information available on the flow rates of these water bodies, making it impossible to calculate the dilution ratio in each case, a factor that influences the assimilation capacity and,

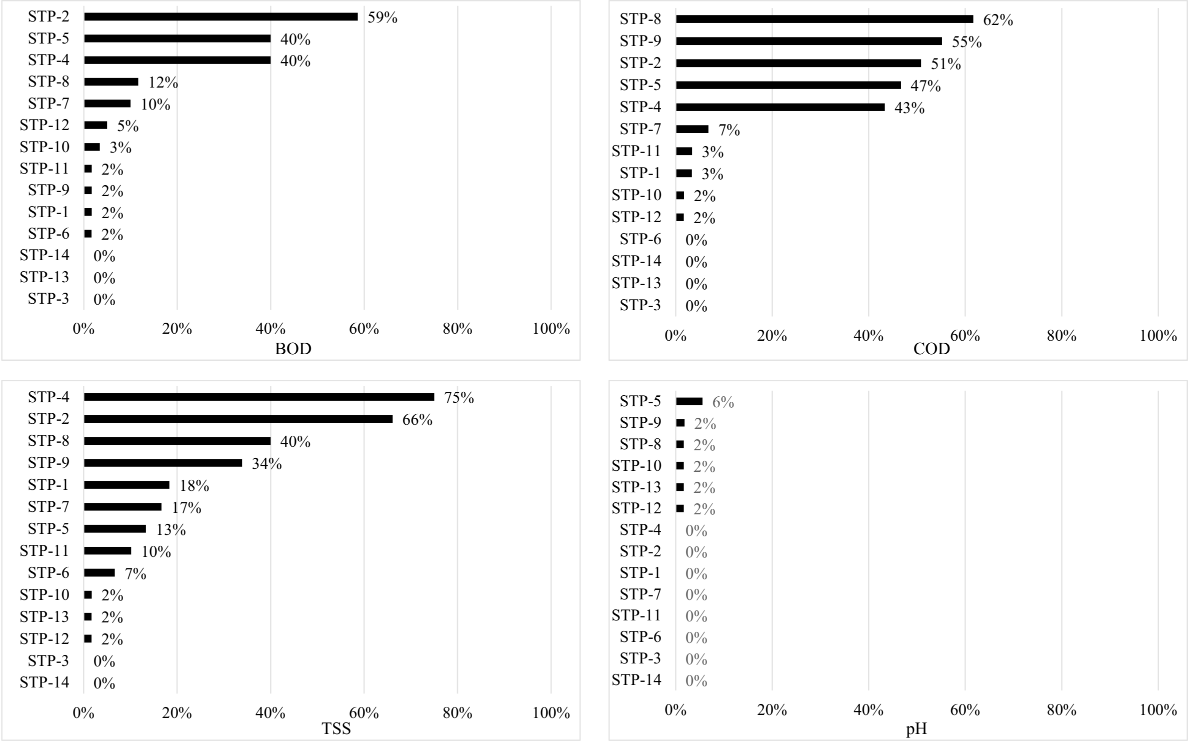


Fig. 4 Violation percentage according to the standards of the legislation for the discharge of effluent from 14 STPs

consequently, the impacts evidenced by the discharge of wastewater. Leonel (2016) identified an increase in BOD, COD, NHx, and *E. coli* concentrations downstream of the release in the recipient bodies with lower dilution ratios.

High concentrations of organic matter were found both upstream and downstream of the discharge points in the Velhas River basin. Comber et al. (2020) found BOD concentrations of less than 4.0 mg/L when assessing receiving water bodies downstream of the effluent discharge points for STPs in England.

With regard to P and *E. coli*, the results reinforce the fact that treatment technologies employed in Brazil are not designed to remove these constituents. Therefore, the release of treated wastewater is reflected in the poor condition of water quality. In the studies carried out in the Velhas River basin, the microbiological parameters of fecal contamination and P were found to be among the three most contaminating elements in relation to local water quality standards (Calazans et al., 2018; Costa et al., 2017; Pinto et al., 2019), demonstrating the low coverage of sewage treatment service and the insufficient treatment used (if any) to remove these compounds (Pinto et al., 2019).

In 21% of the disposals in the Velhas River basin, DO concentrations were determined to be significantly lower downstream compared to those upstream (Table 6). In these receiving water bodies, there were significant increases in BOD and COD, thereby demonstrating the inverse relationship expected of the organic matter parameters with DO (Kumar & Reddy, 2009). However, it is important to note that the critical (lowest) DO concentrations occur downstream of the mixing point (von Sperling & Chernicharo, 2005). It was determined that in many recipient bodies, the concentrations of organic matter were significantly higher downstream; in ecological terms, the most negative impact of water pollution caused by organic matter is the decrease in the level of DO (von Sperling & Chernicharo, 2005). Hence, it is important to monitor the watercourses at other points further downstream to identify the real impacts on DO. On the one hand, Ekka et al. (2006) found no changes in DO concentrations

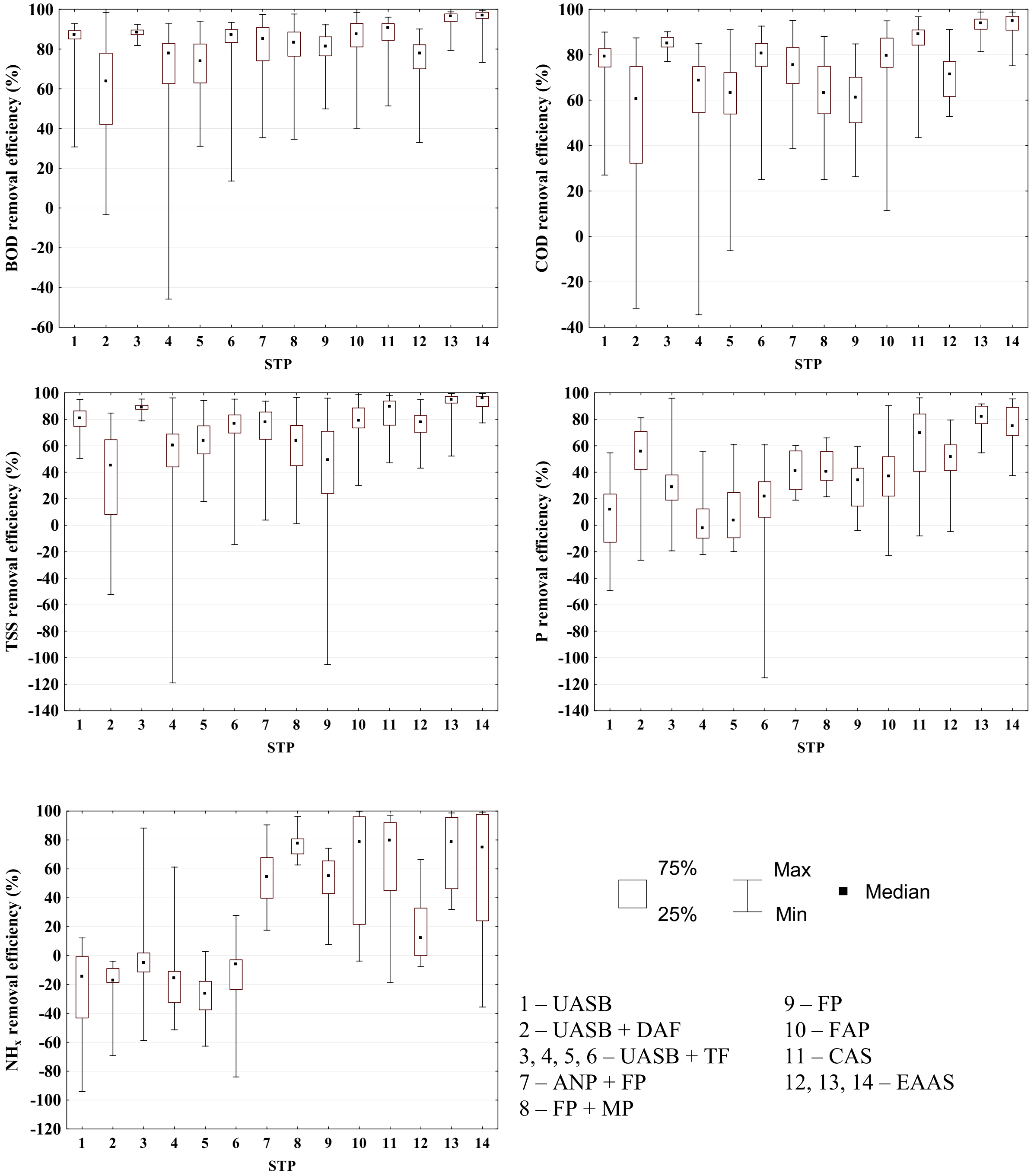


Fig. 5 Load removal efficiencies for selected parameters at 14 STPs in the Velhas River basin

downstream from four disposals of STPs in the USA. Leonel (2016), on the other hand, identified a significant decrease in DO concentrations for all four receiving water bodies of the study, located in a hydrographic basin in the state of São Paulo, Brazil. It is important that other information, such

Table 6 Comparisons of the upstream and downstream values of each disposal in the receiving water bodies of the STPs, using the Mann–Whitney test ($\alpha = 5\%$)

STP	BOD		COD		DO		Turbidity		pH		NHx		NO_3		P		*E. coli*	
	p	Res	*p*	Res	*p*	Res	*p*	Res	*p*	Res	*p*	Res	*p*	Res	*p*	Res	*p*	Res
1	0.3749	< >	0.0700	< >	0.5649	< >	0.1223	< >	0.7672	< >	0.0821	< >	0.6776	< >	0.0757	< >	**0.0029**	↑
2	**0.0000**	↑	**0.0000**	↑	**0.0017**	↓	**0.0000**	↑	**0.0000**	↓	**0.0102**	↑	0.4727	< >	0.0757	< >	**0.0000**	↑
3	0.9724	< >	0.8717	< >	0.2284	< >	0.2366	< >	0.0852	< >	**0.0008**	↑	**0.0046**	↑	**0.0012**	↑	**0.0337**	↑
4	**0.0000**	↑	**0.0000**	↑	**0.0010**	↓	**0.0000**	↑	0.9862	< >	**0.0003**	↑	0.5708	< >	**0.0025**	↑	**0.0000**	↑
5	**0.0000**	↑	**0.0000**	↑	**0.0009**	↓	**0.0007**	↑	**0.0210**	↓	**0.0010**	↑	0.2730	< >	**0.0010**	↑	**0.0000**	↑
6	0.2099	< >	0.2446	< >	0.1759	< >	0.5389	< >	0.7364	< >	0.1509	< >	0.2271	< >	0.1212	< >	**0.0325**	↑
7	**0.0096**	↑	0.1314	< >	0.1963	< >	0.0620	< >	0.4267	< >	0.1306	< >	0.8501	< >	**0.0046**	↑	0.4098	< >
8	**0.0007**	↑	**0.0153**	↑	0.1410	< >	**0.0016**	↑	0.2249	< >	0.1041	< >	0.4274	< >	**0.0233**	↑	**0.0105**	↑
9	**0.0007**	↑	**0.0000**	↑	0.5859	< >	**0.0001**	↑	0.5054	< >	0.1212	< >	0.7913	< >	**0.0058**	↑	**0.0309**	↑
10	**0.0179**	↓	0.2435	< >	**0.0000**	↑	0.0609	< >	**0.0004**	↑	0.7913	< >	1.0000	< >	0.5708	< >	**0.0042**	↓
11	**0.0033**	↓	**0.0358**	↓	**0.0346**	↑	0.9419	< >	0.9378	< >	0.9676	< >	0.4408	< >	0.7353	< >	**0.0001**	↓
12	**0.0000**	↑	**0.0000**	↑	0.0944	< >	**0.0000**	↑	0.7223	< >	**0.0002**	↑	0.0539	< >	**0.0002**	↑	**0.0000**	↑
13	0.3032	< >	0.6264	< >	0.9237	< >	0.3671	< >	0.5868	< >	0.6776	< >	0.6501	< >	0.9699	< >	0.9745	< >
14	0.5696	< >	0.6048	< >	0.2393	< >	0.9577	< >	0.9823	< >	0.4529	< >	0.9699	< >	0.9699	< >	0.3829	< >

Measured values at the upstream and downstream sampling stations are presented in Figs. 6 and 7

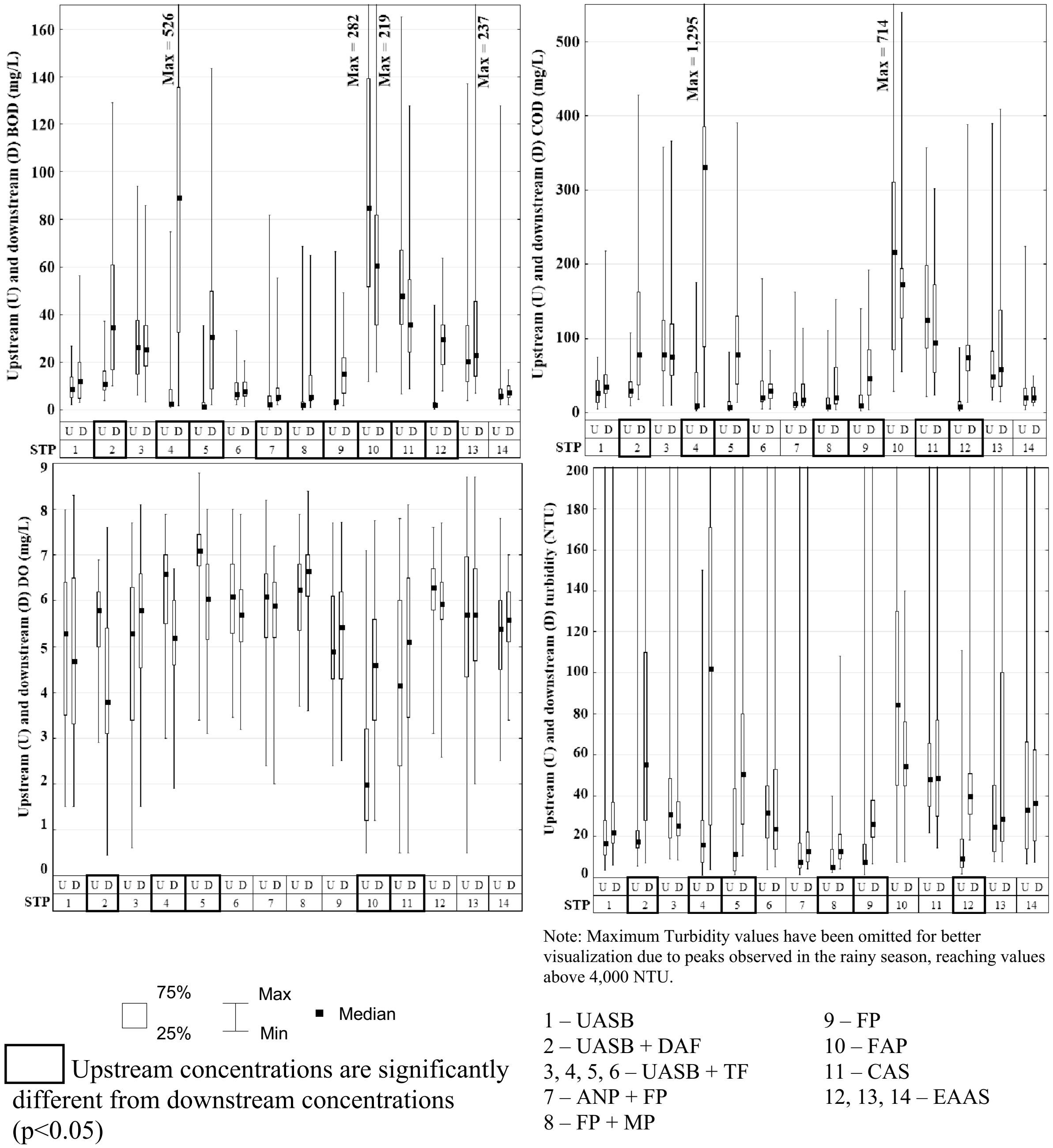
Obs p, *p*-value of the Mann–Whitney test, *Res* result

The underlined and bold values indicate where the difference was significant ($p < 0.05$)

< > No significant difference in values between upstream and downstream

↑ Significantly higher values downstream compared to upstream

↓ Significantly lower values downstream compared to upstream



Note: Maximum Turbidity values have been omitted for better visualization due to peaks observed in the rainy season, reaching values above 4,000 NTU.

☐ Upstream concentrations are significantly different from downstream concentrations ($p<0.05$)

1 – UASB
2 – UASB + DAF
3, 4, 5, 6 – UASB + TF
7 – ANP + FP
8 – FP + MP
9 – FP
10 – FAP
11 – CAS
12, 13, 14 – EAAS

Fig. 6 BOD, COD, DO, and turbidity values upstream and downstream of the STPs disposals

as hydraulic characteristics and the time of sampling activities, is collected and assessed for the receiving water bodies. While dissolved oxygen in a lotic system may be related to the contribution of organic matter, it is not exclusively attributable to this parameter as natural factors including aeration, mixing, and turbulence may influence the results.

In six of the 14 disposals, there was a significant increase in the turbidity values downstream in the receiving bodies (Table 6). However, peaks were observed both upstream and downstream of the

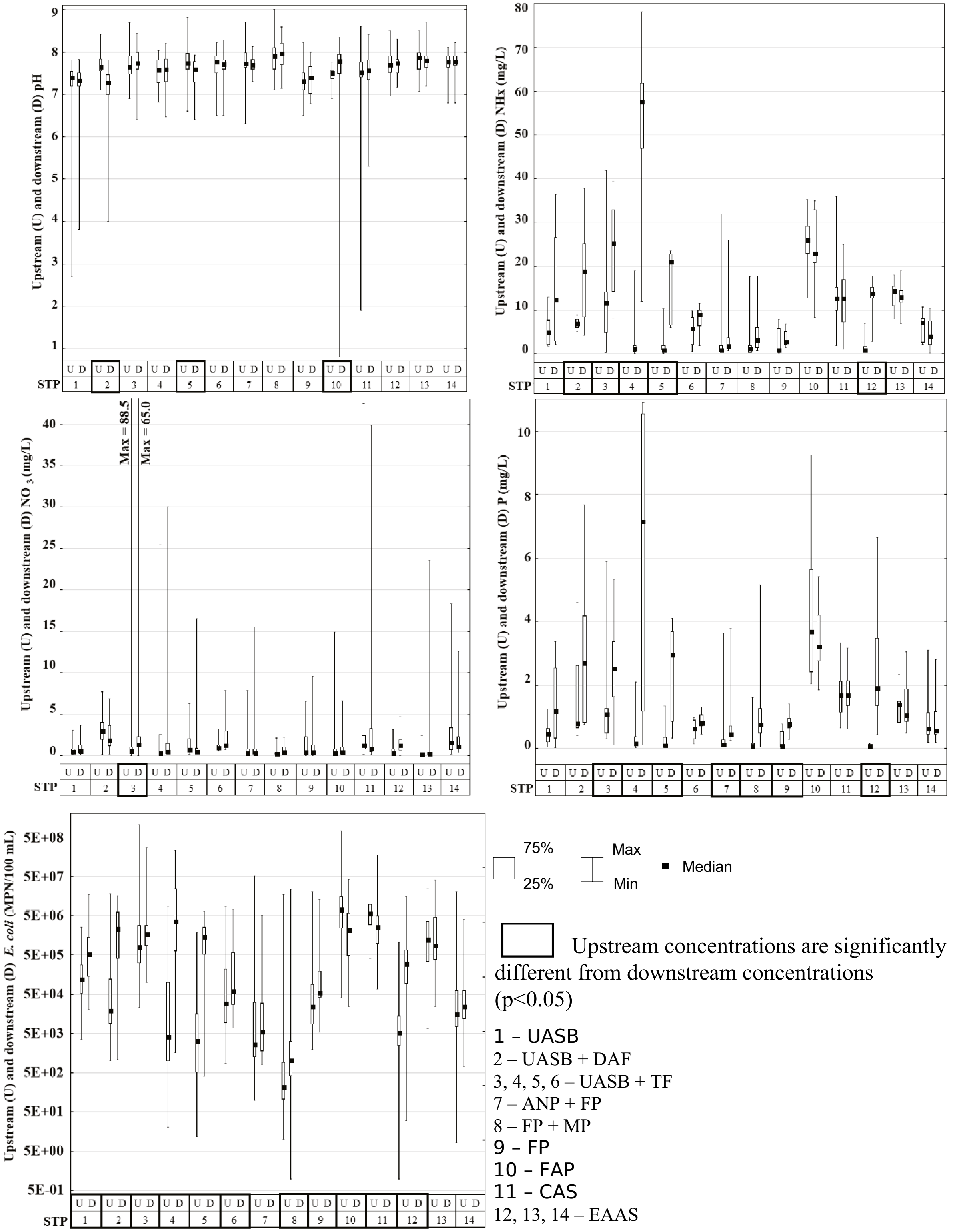


Fig. 7 pH, NHx, NO_3, P, and *E. coli* values upstream and downstream of the STPs disposals

releases, especially in the rainy season, implying that it may be related to other activities carried out in the basin. In 79% of the releases, there was no significant difference in the upstream and downstream pH values. Even in situations in which there was a significant difference, the pH remained close to neutral (Fig. 7), suggesting that there should be no impact on the aquatic environment with respect to this variable. Ekka et al. (2006) likewise found pH values between 6.0 and 9.0 both upstream and downstream of the releases, with no consistent changes arising from treated effluents. In the evaluation of the effluent quality of the STPs in the Velhas River basin, the treated effluent pH was also generally close to neutrality.

Treated effluents from STPs can provide significant inputs of nutrients into water bodies (Kumar & Reddy, 2009). This was identified in the Velhas River basin in terms of NHx and P. Waiser et al. (2011) found significant differences in the concentrations of NHx, oxidized forms of nitrogen (nitrite + nitrate), and P between the upstream and downstream monitoring of a STP disposal in Canada. The authors observed nitrite and nitrate concentrations for more than 100 km downstream of the release and found that they were significantly higher than those of upstream concentrations, reinforcing the importance of monitoring watercourses at points further downstream. Drury et al. (2013) evaluated the effect of the disposal of two STPs of different sizes in the USA and identified, in both rivers, a significant increase in nitrate and phosphate concentrations.

Contrary to what was found in the aforementioned studies, there was no significant difference in nitrate concentrations upstream and downstream of the receiving water bodies (with the exception of STP-3) in the Velhas River basin. The concentrations were low at both monitored points (Fig. 7). In the analysis of the operational performance of the STPs, low concentrations of nitrate were verified in the treated wastewater. In addition, nitrate is more associated with remote pollution (von Sperling & Chernicharo, 2005), which may explain the results found in the basin.

The treatment plants that showed the greatest downstream changes were STP-2, STP-4, and STP-5. There were significant changes to the BOD, COD, OD, turbidity, NHx, and *E. coli* in these three STPs. Furthermore, in the box plots (Figs. 6 and 7), a significant increase in the concentrations of contaminants and a decrease in DO were observed at these plants. In the performance assessment of the STPs, operational problems that reduce the quality of the treated effluent were identified, such as hydraulic overload and instability (related to the large interquartile range of effluent concentrations) in the treatment process.

Better results were observed at STP-13 and STP-14, in which no significant changes in the upstream and downstream values for any parameter were found. It should be noted that STP-13 and STP-14 both presented high effluent quality over the 5-year period. Moreover, in the recipient water bodies of STP-10 and STP-11, there was a significant reduction in the concentrations of organic matter and *E. coli*, as well as a significant increase in downstream DO concentrations (Table 6). The two aforementioned STPs likewise exhibited high effluent quality. It is further inferred that their treated effluents may have contributed to the improvement in the water quality of the receiving bodies (in relation to the analyzed parameters) in part because water upstream of the disposal showed deteriorated quality. It is noteworthy that the municipalities served by STP-10 and STP-11 are both large, with populations of over 200,000 inhabitants in each. As such, the water bodies in these localities receive various contributions from domestic and industrial effluents.

It is observable in the box plots (Figs. 6 and 7) that degraded conditions in terms of the quality of water resources in the basin are found even upstream of the wastewater releases. The results of the degradation state in water quality in the Velhas River basin confirm previous studies carried out in this area, which identified the point source pollution through wastewater disposal as the main source of pollution in the basin (Calazans et al., 2018; Pinto et al., 2019; Trindade et al., 2017). It is further observed that conditions are more critical near large urban centers (Costa et al., 2017; Trindade et al., 2017) and that the BHMR is the region with the highest contamination due to domestic and industrial effluents (Calazans et al., 2018; Costa et al., 2017; Pinto et al., 2019).

Trindade et al. (2017) identified a temporal BOD concentration reduction trend in water quality in the BHMR due to the installation of STPs. However, even after treatment, effluents from many treatment plants in the basin still significantly affect water quality in terms of BOD based on the results of this study. Costa et al. (2017) found results closer to that of the

Table 7 Violation percentage according to the legal water quality standards upstream (U) and downstream (D) of each receiving water body

STP	Rating class	BOD		DO		Turbidity		pH		NHx		NO_3		P		*E. coli*	
		U	D	U	D	U	D	U	D	U	D	U	D	U	D	U	D
1	class 1	**90%**	**97%**	**69%**	**72%**	13%	15%	3%	3%	**70%**	**70%**	0%	0%	**90%**	**90%**	**100%**	**100%**
2	class 2	**90%**	**100%**	23%	**73%**	3%	30%	0%	4%	**100%**	**100%**	0%	0%	**100%**	**100%**	**97%**	**100%**
3	class 3	**92%**	**93%**	33%	14%	3%	3%	0%	0%	**80%**	**100%**	11%	11%	**100%**	**95%**	**100%**	**100%**
4	class 2	41%	**93%**	20%	32%	7%	**52%**	0%	0%	20%	**100%**	10%	10%	**70%**	**100%**	**74%**	**100%**
5	class 2	17%	**93%**	7%	21%	10%	17%	0%	0%	30%	**100%**	0%	10%	50%	**100%**	**63%**	**97%**
6	class 2	**68%**	**82%**	11%	25%	14%	11%	0%	0%	**60%**	**90%**	0%	0%	**100%**	**100%**	**96%**	**100%**
7	class 2	28%	**55%**	24%	24%	3%	3%	0%	0%	20%	40%	0%	10%	**60%**	**100%**	**76%**	**90%**
8	class 2	17%	**57%**	17%	13%	0%	3%	0%	0%	20%	**70%**	0%	0%	50%	**90%**	23%	50%
9	class 2	23%	**80%**	**52%**	38%	7%	3%	0%	0%	30%	**60%**	0%	0%	40%	**100%**	**100%**	**100%**
10	class 2	**100%**	**100%**	**97%**	**62%**	34%	14%	0%	3%	**100%**	**100%**	10%	0%	**100%**	**100%**	**100%**	**100%**
11	class 3	**98%**	**98%**	50%	31%	4%	10%	3%	3%	**75%**	**60%**	15%	15%	**100%**	**100%**	**100%**	**100%**
12	class 2	14%	**100%**	3%	10%	3%	10%	0%	0%	10%	**90%**	0%	0%	50%	**100%**	**83%**	**97%**
13	class 2	**93%**	**100%**	32%	31%	14%	24%	0%	0%	**100%**	**100%**	0%	10%	**100%**	**100%**	**100%**	**100%**
14	class 2	**69%**	**73%**	33%	20%	17%	21%	0%	0%	**89%**	**67%**	10%	10%	**100%**	**100%**	**93%**	**97%**

Obs The underlined and bold values indicate violation percentages > 50%

present study, in which most of the basin monitoring stations showed no temporal trend for BOD violation percentages in addition to all other parameters under analysis. Dantas et al. (2019) found only 25% of monitoring stations with a temporal trend in the concentrations of the fecal contamination indicator. According to these studies, the results indicate the persistent degradation of water resources in the basin over the years.

Table 7 shows the violation percentage based on the legislation for water quality standards (Table 4) upstream and downstream of the effluent discharge point in each receiving water body. The parameters that had the highest percentages of violation were BOD, NHx, P, and *E. coli*. In many cases, the violation percentage increased downstream compared to upstream; however, violation percentages were also high upstream of the discharge point. With respect to P and *E. coli*, in 79% and 64% of the STPs, respectively, 100% of violations occurred downstream of the discharge point.

Conclusions

From the various examinations carried out using monitoring data of influent and effluent concentrations of STPs operating at full-scale in the Velhas River basin, the situation experienced by the systems during the study period was determined.

Significant differences were identified in the operational performance of the treatment plants for all research parameters. The results of the current study should not be generalized for all STPs of the same size or with the same types of treatment, since STPs can exhibit performances lower than the potential of the employed treatment technologies due to operation and design difficulties.

This study advances wastewater treatment research because it analyses the receiving water bodies, which have not been collectively evaluated in most studies on the operational performance of full-scale treatment systems. In Brazil, the usual practice is to release effluents into watercourses; hence, it is important to ensure that the impact of raw sewage release is minimized by adopting appropriate treatment practices. However, in several cases, worse conditions were observed downstream compared to those upstream, even when the effluents discharged into the water bodies of the basin were treated. This confirms that the implementation of wastewater treatment at only the secondary level, which is observed in municipalities in Brazil, is insufficient for the removal of nutrients and coliforms — the main components in which a significant difference was observed downstream of the receiving water bodies.

Despite the great economic development in the BHMR and in the Velhas River basin by Brazilian standards, STPs with inefficient performance have been identified which significantly alter the quality of their waters.

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Author contribution All authors contributed to the study conception and design. All authors read and approved the final manuscript.

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Data Availability The data that support the findings of this study are available from the sanitation service provider, but restrictions apply to the availability of these data, which were used under license for the current study, and so are not publicly available. Data are however available from the authors upon reasonable request and with permission of the sanitation service provider.

Declarations

Competing interests The authors declare no competing interests.

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